



AFRL-RX-WP-TP-2012-0235

**MICROSTRUCTURE-INDUCED PHONON FOCUSING
EFFECTS AND OPPORTUNITIES FOR IMPROVED
MATERIAL QUANTIFICATION (POSTPRINT)**

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Metals Branch

Metals, Ceramics & Nondestructive Evaluation Division

FEBRUARY 2012

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REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YY) February 2012		2. REPORT TYPE Technical Paper		3. DATES COVERED (From - To) 1 November 2011 – 1 November 2011		
4. TITLE AND SUBTITLE MICROSTRUCTURE-INDUCED PHONON FOCUSING EFFECTS AND OPPORTUNITIES FOR IMPROVED MATERIAL QUANTIFICATION (POSTPRINT)				5a. CONTRACT NUMBER In-house		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER 62102F		
6. AUTHOR(S) James L. Blackshire				5d. PROJECT NUMBER 4349		
				5e. TASK NUMBER N/A		
				5f. WORK UNIT NUMBER LM106500		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Metals Branch (AFRL/RXLM) Metals, Ceramics & Nondestructive Evaluation Division Materials and Manufacturing Directorate				8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-RX-WP-TP-2012-0235		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Materials and Manufacturing Directorate Wright-Patterson Air Force Base, OH 45433-7750 Air Force Materiel Command United States Air Force				10. SPONSORING/MONITORING AGENCY ACRONYM(S) AFRL/RXLM		
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-RX-WP-TP-2012-0235		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.						
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15. SUBJECT TERMS microstructure, ultrasound scattering, phonon focusing, scanning laser vibrometry						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT: SAR	NUMBER OF PAGES 8	19a. NAME OF RESPONSIBLE PERSON (Monitor) Dallis Hardwick	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include Area Code) N/A	

Microstructure-Induced Phonon Focusing Effects and Opportunities for Improved Material Quantification

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Abstract—It is well known that single-crystal materials such as silicon have anisotropic elastic properties which depend on crystalline direction, causing the characteristic properties of a propagating elastic wave to have spatial and directional dependencies. As a result, variations in the speed and energy flux of an elastic waves propagating in a single crystal material typically produce spatial patterns, which can be used to infer the internal structure of a crystalline material. For polycrystalline materials, similar effects can be manifested when textured or single phase, equiaxed grains are involved, and coherent wave interference processes exist. Three examples of this are presented in this paper, where the propagation of longitudinal waves within single crystal silicon, textured titanium, and polycrystalline nickel materials are characterized using scanning laser vibrometry in a thru-transmission detection mode. By measuring and studying the resulting patterns, it is anticipated that inversion methods can be developed for the quantitative evaluation of single crystal and polycrystalline materials.

Index Terms— Microstructure, Ultrasound Scattering, Phonon Focusing, Scanning Laser Vibrometry

I. INTRODUCTION

THE interaction of ultrasound with single crystal and polycrystalline materials has been an active area of research for many decades. The measurement and imaging of phonon focusing effects, in particular, has resulted in many important advances in the understanding of phonon interactions with electrons, electron-hole pairs, defects, superlattices, and interfaces [1-4]. As pointed out by Hauser et. al. [3], and more recently by Solodov et. al. [4], much of the early research in this area has focused on ballistic, high-frequency, incoherent phonons, where phonon-phonon and electron-phonon scattering processes placed limits on the methods applicability. More recently, the advantages of using lower-frequency, coherent ultrasonic waves and phonons has suggested that phonon-focusing methods may be extended to nondestructive evaluation, structural health monitoring, and material property characterization applications [4-10], where the imaging of bulk, surface, and guided wave interactions

with anisotropic material properties can provide critical information about the micro-, meso-, and macro-scale property features and inherent spatial variability in those properties.

In the present effort, an exploration of low-frequency, bulk-wave interactions with single crystal and polycrystalline materials was undertaken to better understand potential opportunities for improved nondestructive characterization of the internal structure of those materials. A need currently exists for quantifying and mapping spatial variations in material properties in 2D and 3D for advanced aerospace materials including both superalloy metallic materials and advanced nonmetallic composite and hybrid materials. The use of phonon-focusing and coherent energy field transport phenomena is, therefore being considered for microstructure quantification in engine superalloy materials, where recent observations of anisotropic grain features imparting phase and amplitude variations in pitch-catch, bulk wave ultrasonic measurements have been reported [8,10]. To observe and resolve key spatial and temporal features in ultrasonic signal content, the current effort utilizes a scanning laser vibrometry system to map energy field variations in thru-transmission mode with traditional contact transducer excitation in the 5-10 MHz frequency range.

II. PHONON FOCUSING EFFECTS IN SINGLE CRYSTAL AND POLYCRYSTALLINE MATERIALS

A. Physics of the Problem

The phenomena of phonon focusing has been studied extensively and descriptions of the theoretical basis for the effect have been covered elsewhere [1,2]. In general, the causes of phonon focusing involve elastic anisotropy in a material system that strongly affects the propagation of acoustic waves in a solid, which are manifested in changes in wave velocity, energy flux, and wave polarization with propagation direction. As depicted schematically in Figure 1, the flow of energy for an isotropic material propagates away from a point source excitation uniformly in all directions, while the energy flow for an anisotropic material propagates preferentially in certain directions depending on the specific material, its fundamental crystalline type, and the relative orientation of the crystal with respect to the elastic wave field

Manuscript received April 12, 2011.

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direction. In pitch-catch ultrasonic detection, localized regions can form with very intense energy flux levels, while other regions can receive very little energy, where the intense regions represent caustics in the photon flux predicted by classical theory [1,2]. In effect, local variations exist in the arrival times of various propagating modes/waves with the same group-velocity direction, which constructively or destructively interfere at spatially-resolved detection points.

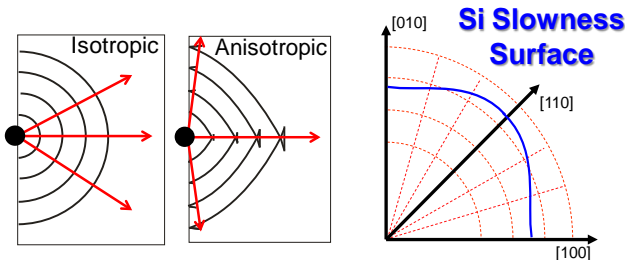


Fig. 1. Schematic diagrams of energy flow for isotropic and anisotropic cases (left and center), and slowness surface for single crystal silicon (right).

The elastic modulus properties of single crystal silicon, for example, vary from 130 GPa for the [100] crystalline direction, to 170 GPa for the [110] direction, to 189 GPa for the [111] direction (in the crystallographic (100)-plane). This in turn causes elastic wave arrival times to vary, as depicted in the slowness surface schematic diagram in Figure 1, where arrival times depend on the specific crystallographic planes, and their orientation relative to the propagating ultrasonic modes. For polycrystalline materials, many grains exist with varying crystallographic orientations. The propagation of modes and coherent energy field flow from grain to grain causes similar energy flux variations, which can be detected and imaged with an appropriate measurement system [8,10].

B. Experimental Measurement Approach

The observation of phonon focusing effects has been accomplished using many different measurement approaches [1,2]. For nondestructive evaluation purposes, the use of contact and immersion ultrasonic transducers is desired, with typical sensor sizes on the order of millimeters to centimeters. Depending on the ultrasonic frequency, material type, material size/thickness, and mode type, phonon focusing effects can occur with spatial features in the micron to millimeter size range when using a pitch-catch transmission method [8,10].

In order to observe the detailed spatio-temporal effects of phonon focusing, a high resolution and non-perturbing probe system has proven to be useful [8,10]. In the present study, a scanning laser vibrometry detection approach was used as depicted schematically in Figure 2. The system uses a Polytec OFV-505 vibrometry system with a frequency bandwidth of 20 kHz – 35 MHz. Focused spot sizes of 10 microns provide adequate spatial resolution measurement capabilities for most practical applications. By scanning the laser probe beam relative to the back surface of a sample, an image or mapping of an ultrasonic field can be made for an excitation on the opposite surface of a material system. In the present case,

contact single crystal transducers were used for excitation with frequencies in the 5-10 MHz range, and transducer diameters of 0.5 inches.

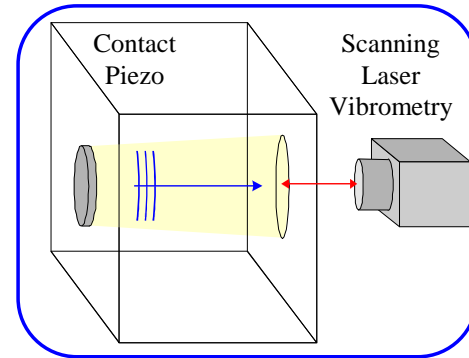


Fig. 2. Schematic of measurement approach involving a contact transducer excitation on the left and scanning laser vibrometry detection on the right.

C. Measurements in Single Crystal Silicon

An example of measurement results obtained for a set of 38.1 mm long x 20 mm diameter single crystal silicon samples is provided in Figure 3. Three separate samples were obtained with specific crystallographic cuts made along the sample length for the [100], [110], and [111] orientations. A digital picture of the [100] sample is provided in the upper left portion of Figure 3.

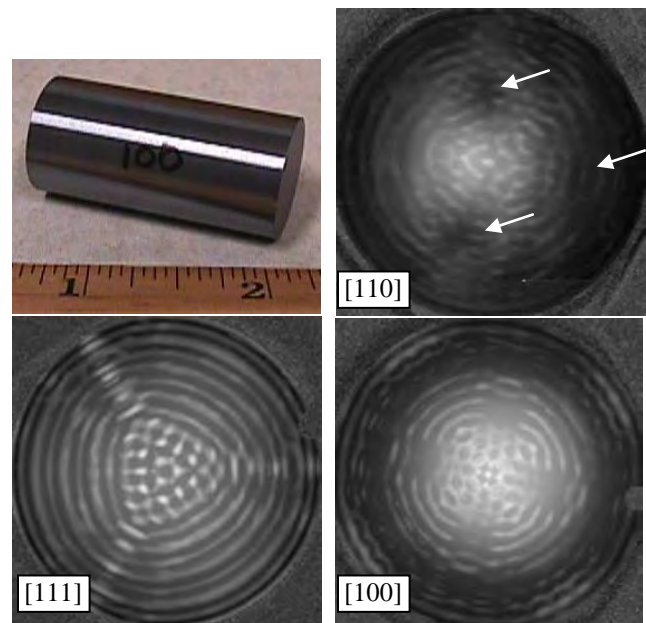


Fig. 3. Digital image of [100] single crystal silicon sample (upper left), and measurement results for [110], [100], and [111] samples (clockwise images from upper right).

As described in the previous section, a single crystal 5 MHz longitudinal cut transducer was bonded to the left surface of the sample and was used for bulk wave excitation through the length of the sample, and scanning laser vibrometry

measurements were made on the opposite right surface of the sample. The scan dimensions in the three measurement images depicted in Figure 3 were 20 mm x 20mm, with a scan resolution step size of 100 microns. Very distinct energy field measurements can be noticed in each case, where the peak-to-peak, out-of-plane displacement of the longitudinal wave are being depicted in the measurements. The images are similar in qualitative nature to previously published examples of phonon focusing effects in single crystal silicon samples [1-3]. In particular, the [111] result is expected to have 3-fold symmetry features, which are very evident in the measurement example (lower left image result in Figure 3). Similarly, the [100] result is expected to result in 4-fold symmetry features, which is the general case depicted in the measurement results (lower right image in Figure 3). A more complex pattern can be noticed for the [110] result, where a predominant 4-fold symmetry is observed, but subtle 3-fold symmetry effects can also be noticed, which result in an elongated pattern, and three dark energy field lobes can be noticed as indicated by the arrows in the figure. The important point to be made is that the internal crystallographic structure imparts specific ultrasonic energy field patterns that can be useful in quantifying the internal structure of the material system.

D. Measurements in Textured Titanium Materials

An example of a more complex polycrystalline material system is depicted in Figure 4, where a rectangular block (25.4mm x 50.8mm x 76.2mm) of Ti-6Al-4V titanium was studied, where polycrystalline texture effects were known to exist. In such a case, oriented crystal grains cluster together in directional colonies, creating large-grain preferred orientation effects with respect to the crystallographic elastic properties [8,9].

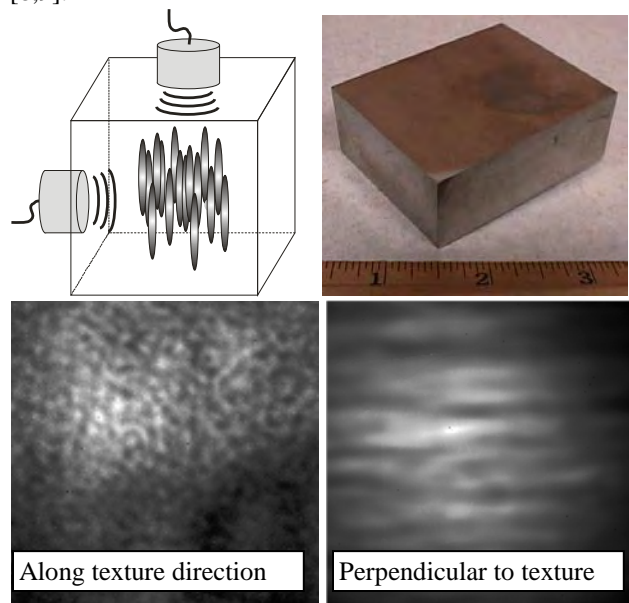


Fig. 4. Schematic diagram of an elongated, textured grain structure and probing directions in titanium (upper left), digital image of sample (upper right), and measurement results (bottom left and right).

The measurement results in Figure 4, which involved a 5 MHz longitudinal wave propagation measured over a 10 mm x 10 mm area, show distinct pattern variations for probe conditions aligned with the texture effects, and aligned normal to the texture effects. In particular, the elongated grains result in colonies that are largely cigar-shaped or cylindrical in their form, where elastic energy propagating along the length of these features would result in circularly symmetric phase and amplitude features. When imaged as a peak-to-peak image field as depicted in Figure 4, the texture effects result in primarily circular lobes of energy. For probes aligned normal to the texture direction, the energy field interacts with vertically-oriented features, which correlate well with the observations in the bottom right image of Figure 4. The ability to map and image texture effects is of considerable interest in the nondestructive evaluation of aerospace superalloy materials.

E. Measurements in Dual-Microstructure Nickel Materials

A final example of an additional complex polycrystalline material system is depicted in Figure 5, where microscopy and ultrasonic imaging results are provided for a dual microstructure nickel material system. The grain sizes and distribution in this particular material system were engineered to have grain sizes of 100 microns in one region of the material and 10 microns in another region, where the nondestructive evaluation and quantification of microstructure features is needed.

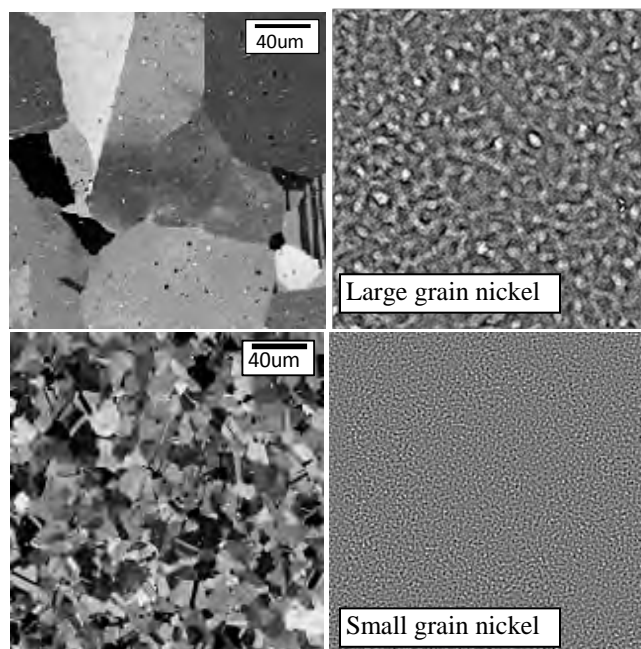


Fig. 5. Microscopy images of grain structure in dual-microstructure nickel material system (left), and corresponding ultrasonic imaging results for the large (top right) and small (bottom right) grain regions.

The measurement results in Figure 5 depict local variations in amplitude and phase, which when viewed as a peak-to-peak

displacement field images suggest that microstructure grain size estimates may be possible using the approach described previously. The measurements in the present example involved a 5 MHz longitudinal waves imaged over a 5 mm x 5 mm region. Preliminary assessments of the size scales of the measurement features depicted in Figure 5 correlate well with the actual microstructure sizes depicted in the microscopy images in the figure. The results are very encouraging with respect to potential nondestructive evaluation measurement capabilities for mapping and quantifying microstructure sizes in complex microstructure systems.

III. CONCLUSION

Measurement results were provided for three different material systems involving the imaging of phonon focusing and coherent elastic energy field effects. Variations in the local speed and energy flux of the elastic waves propagating in the material systems were studied using thru-transmission ultrasound and scanning laser vibrometry detection. In particular, the propagation of longitudinal waves within single crystal silicon, textured titanium, and polycrystalline nickel materials were characterized, where spatially varying energy field patterns provided insight into the material state features of the different material systems. By measuring and studying the resulting patterns, it is anticipated that inverse methods can be developed for quantitative evaluation of single crystal and polycrystalline materials.

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development to uncover and mitigate confounding factors (structural geometry and material state variations) for improved detection, location, and quantification of damage in aerospace systems.